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Effective solar radiation based benefit and cost analyses for solar water heater development in Taiwan

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ABSTRACT

To reduce greenhouse gases emissions, promoting solar water heaters (SWHs) has become an essential national policy in Taiwan. To implement this policy effectively, the applicability of SWHs in different regions must be analyzed. Previous studies generally performed SWH benefit–cost analyses based on total annual solar radiation; however, this method may overestimate energy production benefits because, for an SWH, the solar energy captured today cannot be preserved. Therefore, this study proposes the concept of effective solar radiation (ESR), which is based on potential heat output estimated using tap water temperature and solar radiation in each region. The benefits of SWHs are then assessed based on the number of effective days and ESR, instead of using total annual solar radiation. A procedure is established to evaluate the applicability of SWHs in each region based on proposed benefit–cost analyses. Possible outcomes of a national SWH program are estimated. The sensitivities of essential factors, including collector efficiency, installation cost, and discount rate, are also analyzed. Analytical results show that the ratios of ESR to total annual solar radiation for regions in Taiwan are about 82–89%. The payback periods vary at 6–15 years for different regions and heater types being replaced. The national program is expected to reduce greenhouse gases emissions by approximately 150,000 tons eCO_2 annually.

Contents

Abbreviations: SWH, solar water heater; ESR, effective solar radiation; E-day, effective day; GHGs, greenhouse gases; TSP, total suspended particles; LPG, liquefied petroleum gas; AR, abundant radiation; HR, high radiation; MR, moderate radiation; SI, small island.

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1. Introduction

Taiwan imports 99% of its energy [1], and emissions of greenhouse gases (GHGs) per capita markedly exceed the global average. Therefore, the development of renewable energies, such as solar energy, has become a national policy in Taiwan [2]. However, the amount of solar radiation varies among regions in Taiwan. For example, the amount of solar radiation in southern Taiwan is roughly 1.5 times higher than that in northern Taiwan [3]. Therefore, the applicability and potential benefits of solar water heaters (SWHs) in different regions must be analyzed.

Several studies (e.g., Haralambopoulos et al. [4]; Diakoulaki et al. [5]; Kaldellis et al. [6]) evaluated the applicability of various SWH development programs based on benefit–cost analyses, and solar radiation was the major factor considered by these studies. Total annual solar radiation was used to estimate energy production benefit. However, for an SWH, since solar energy captured today cannot generally be stored for later use [4], an analysis based on total annual solar radiation may overestimate energy production benefit. For instance, an SWH with a tank volume of 250 L and 4 m^2 collector surface requires approximately 16 MJ of solar radiation to heat water to 55 °C [7] when tap-water temperature is 25 °C and collector efficiency is 50%. If actual solar radiation today is 20 MJ, the surplus solar radiation of 4 MJ cannot be saved unless an additional water tank or storage battery is installed. However, an additional tank or battery is generally not cost-effective for an SWH. An enhanced method based on required daily solar radiation and number of SWH effective days is applied in this study to improve benefit–cost analyses.

Furthermore, ambient temperature varies significantly in different months and regions, as does the temperature of tap water. For example, water temperature in winter is low and heating this water requires more solar radiation than in summer. Thus, the amount of daily solar radiation required to heat water to a desired temperature varies. Most previous studies did not consider temperature variations, and the proposed SWH benefit–cost analysis method is thus modified further to consider this variation. In addition to analyzing the applicability of SWHs based on the proposed benefit–cost analytical method, identifying potential environmental benefits is necessary for assessing a regional SWH program. Since SWHs can reduce consumption of other energies, such as electricity, fossil fuels, and natural gas, the potential environmental benefits of SWHs include reductions in emissions of GHGs, NOx, and total suspended particles (TSP) [5,8,9], generated by replaced energies, subsequently reducing external costs incurred for these pollutant emissions. Estimating potential environmental benefits is therefore necessary when analyzing the true benefits and costs of developing SWHs.

The benefits and costs for implementing Taiwan's national SWH program are assessed. The sensitivities of the effects of major variables, such as collector efficiency, installation cost, and discount rate, are also analyzed and compared. Study results will help policy-makers determine how the effective solar radiation, regional characteristics, and other variables affect the applicability, benefits, and costs for a national SWH program.

The remainder of this paper is organized as follows. The study area is first introduced, and the SWH region is then described. Next, the proposed effective day and effective solar radiation (ESR) are explained. How to estimate SWH benefits, costs, and the payback period is described and used to assess the national SWH program. Finally, sensitivity analyses of various parameters are presented.

2. Study area

Since the Tropic of Cancer crosses south-central Taiwan, solar radiation in Taiwan is considerable, and Taiwan is a good candidate for SWHs. However, as Table 1 lists, significant variation exists in the amount of solar radiation in different regions, such that the applicability of SWHs in different regions varies too. Appropriate regional division is thus needed to facilitate planning of SWH development strategies. Furthermore, the difference between solar radiation in both July and December is also significant. Therefore, seasonal solar radiation variations must be considered when analyzing the applicability of a regional SWH program.

Haralambopoulos et al. [4] and Kaldellis et al. [6] divided regions in Greece based primarily on the amount of solar radiation. However, regions divided based on the amount of solar radiation may not match administrative boundaries and may cause difficulties in SWH programs because an SWH development policy requires the participation of local governments. Therefore, this study delineated regions based on both the amount of solar radiation and the administrative boundaries. As listed in Table 1, Taiwan is divided into four regions: the abundant radiation (AR) region, the high radiation (HR) region, the moderate radiation (MR) region, and the small island (SI) region.

3. Effective day and effective solar radiation

Total annual solar radiation was often used to estimate solar energy production (e.g., Kaldellis et al. [6], Li and Yang [10]), but it may overestimate the energy saving of a SWH due to ESR. Furthermore, solar radiation varies for different regions and seasons in Taiwan; thus, Taiwan's temporal and spatial characteristics must be analyzed. An enhanced method is thus proposed based on ESR, regional amounts of solar radiation, and tap water temperatures.

For an SWH, surplus solar radiation cannot be saved and, thus, excessive solar radiation cannot result in additional energy savings. Furthermore, tap water temperature significantly affects the amount of solar radiation required to heat water to a desired temperature. Cold tap water requires more solar radiation to heat than warm tap water. To evaluate the applicability of SWHs in each region, this study proposed two new indexes, the annual ratio of effective days (E-days) and annual ESR, to assess potential energy savings from an SWH. The values of both indexes are estimated based on tap water temperature and daily solar radiation in each region. An E-day is a day on which solar radiation exceeds the minimum required solar radiation, and the ESR is total annual effective solar radiation used by an SWH. These two indexes are described as follows.

3.1. Annual E-day ratio

Before describing this index, minimum required solar radiation is defined. An SWH requires sufficient solar radiation to heat tap water. When solar radiation is insufficient, an SWH cannot heat enough hot water for daily uses and requires other energies to heat tap water to a desired temperature—55 °C in this study. Thus, the minimum required solar radiation is the amount of solar radiation required by an SWH to heat tap water to the desired temperature. It is determined based on tap water temperature and SWH specifications, and is estimated by the following equation [11].

$$S_{z,d}^{\min} = \frac{V \cdot Ds \cdot H \cdot \Delta t_{z,d}}{\gamma_{\mathrm{SWH}} \cdot A} \qquad (1)$$

where $S_{z,d}^{\min}$ is minimum required solar radiation (MJ/m^2) for day d in region z; V is the volume of an SWH storage tank (L); Ds is water density (kg/L); H is the specific heat (MJ/kg °C) of water; Δt_d

Table 1
Average solar radiation of four regions during 2006–2008.

Region	Range (MJ/m²)	Weather station code	Annual total solar radiation (MJ/m²)	Mean daily solar radiation (MJ/m²)	
				July	December
Abundant radiation (AR)	5000–6000	TC	5286	18.4	12.3
		CY	5857	19.7	13.1
		KS	5174	17.7	10.6
		PD	5093	16.7	10.9
		TD	5551	23.1	10.5
High radiation (HR)	4000–5000	HC	4433	19.2	8.3
		NT	4262	14.7	10.9
		TN	4961	16.9	10.6
Middle radiation (MR)	3000–4000	TP	3841	15.7	7.3
		IL	3758	19.2	5.6
		HL	3953	21.0	7.9
Small island (SI)	3000–5000	KM	4624	18.8	9.3
		PH	4080	17.8	8.1
		MT	3973	18.8	7.0

is temperature difference (°C) between the hot water heated by an SWH and tap water on day d; γ_{SWH} is collector efficiency of an SWH; and A is surface area of a solar collector (m²).

When available solar radiation on one day exceeds $S_{z,d}^{\min}$, an SWH can heat tap water to the desired temperature, and the day is regarded as an E-day. Since solar radiation varies among regions, the number of effective days also differs among regions. The annual E-day ratio is then calculated using the following equation:

$$\text{For} \quad DR_{z,d} > S_{z,d}^{\min}, \quad E_{z,d} = 1,$$
$$\text{For} \quad DR_{z,d} < S_{z,d}^{\min}, \quad E_{z,d} = 0,$$

$$RE_z = \frac{\sum_{d=1}^{Y} E_{z,d}}{Y} \tag{2}$$

where $DR_{z,d}$ is solar radiation on day d for region z; $E_{z,d}$ is a binary variable indicating whether day d in region z is an E-day; RE_z is the annual E-day ratio in region z; and Y is the number of days in a study year (usually 365 days). E-days are those days on which an SWH provides sufficient hot water using only solar energy. The annual E-day ratio is an useful index when assessing the applicability of SWHs in different regions. The $S_{z,d}^{\min}$ value is estimated for a typical family SWH with a 250-L storage tank providing 55 °C water. The solar collector surface area is 4 m² and collector efficiency is 50%, the minimum acceptable efficiency in Taiwan [12]. Regional tap water temperatures are estimated based on data obtained by Chang [13]. Fig. 1 shows the $S_{z,d}^{\min}$ values for the typical SWH in different months and regions in Taiwan. The $S_{z,d}^{\min}$ value in winter is higher than that in summer because tap water in winter is colder than in summer and, thus, requires more solar radiation to heat to the desired temperature.

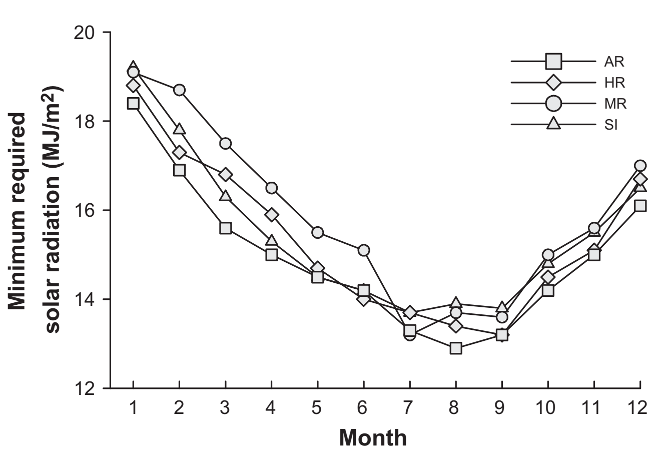


Fig. 1. Minimum required solar radiation for different regions.

Fig. 2 shows the annual and monthly E-day ratios of different regions based on 2008 data. Fig. 2(a) presents the annual E-day ratios for the four regions; all exceed 30%. The annual E-day ratio for the AR region, 50%, is significantly higher than those for other regions, and is 19% higher than that for the MR region (31%).

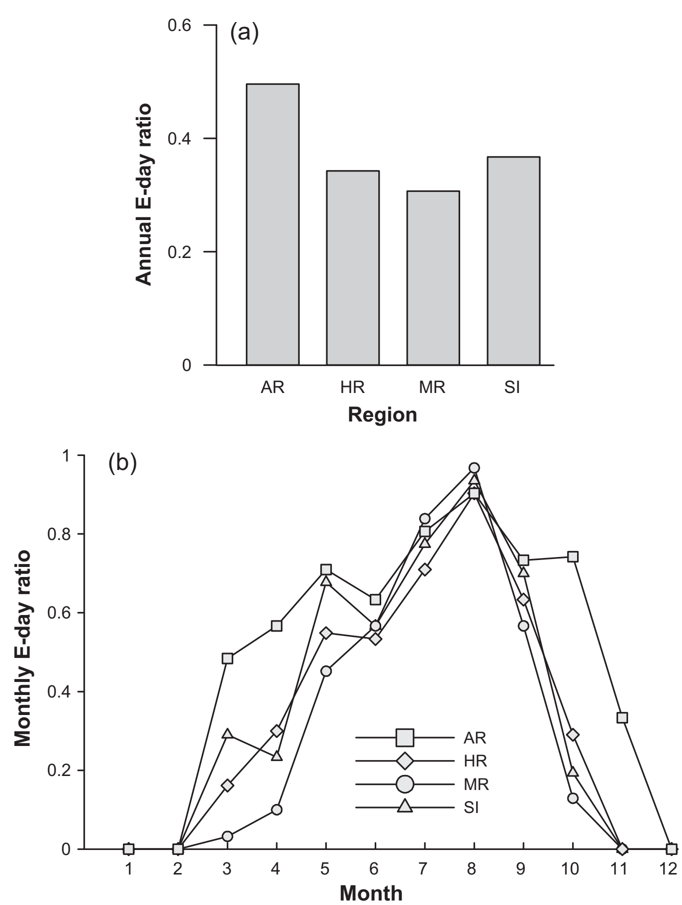


Fig. 2. E-day ratios for different regions: (a) annual E-day ratio and (b) monthly E-day ratio.

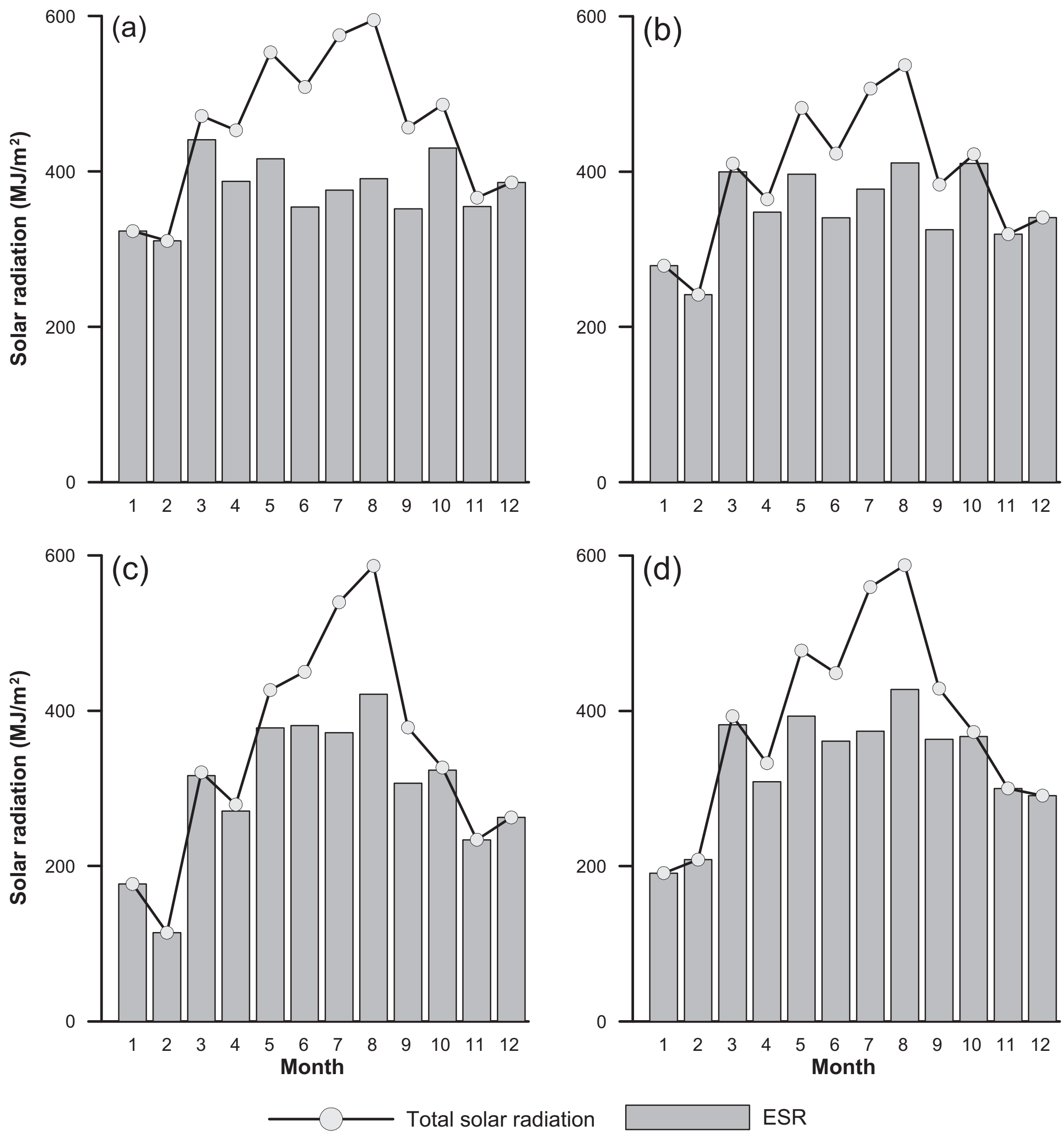


Fig. 3. Monthly effective solar radiation in the (a) AR, (b) HR, (c) MR, and (d) SI regions.

Since summer solar radiation is abundant and the required $S_{z,d}^{\min}$ is low, the monthly E-day ratios in summer, as illustrated in Fig. 2(b), are markedly higher than those in other seasons. Because winter is typically cloudy, rainy, and cold in some regions, and the amount of solar radiation and tap water temperature are low, monthly E-day ratios for the four regions in December, January, and February are 0%. A low annual E-day ratio indicates that a significant amount of supplemental energy, such as natural gas or electricity, is needed to heat tap water to the desired temperature on non-E-days.

3.2. Annual effective solar radiation

To analyze the benefits and costs of SWHs, a novel index, annual ESR, is proposed. The annual ESR index is determined by the following equations:

$$\begin{aligned} &\text{For}\quad E_{z,d}=1, \quad ER_{z,d}=S_{z,d}^{\min}, \\ &\text{For}\quad E_{z,d}=0, \quad ER_{z,d}=DR_{z,d}, \end{aligned} \tag{3}$$

$$ESR_z = \sum_{d=1}^{Y} ER_{z,d} \tag{4}$$

$$RESR_z = \frac{ESR_z}{\sum_{d=1}^{Y} DR_{z,d}} \tag{5}$$

where $ER_{z,d}$ is ESR on day d in region z; ESR_z is the annual ESR in region z; and $RESR_z$ is the ratio of ESR to total solar radiation in region z. When day d is an E-day and $DR_{z,d} > S_{z,d}^{\min}$, surplus solar radiation does not provide additional energy savings. Therefore, in Eq. (3), when $E_{z,d} = 1$, $ER_{z,d} = S_{z,d}^{\min}$, not $DR_{z,d}$. When $DR_{z,d} < S_{z,d}^{\min}$, energy saving is the amount of solar energy produced by $DR_{z,d}$. Thus, $ER_{z,d} = DR_{z,d}$ in Eq. (3) when day d is not an E-day. The ESR_z value is then the sum of all $ER_{z,d}$ values in a study year.

Fig. 3 compares the monthly ESRs for different regions. The ESR in summer is not significantly higher than that for other seasons in the AR and HR regions. Although solar radiation is high in summer, energy savings for heating water are low as the temperature of tap water in summer is also high. In winter, relatively more solar radiation is needed to heat water to the desired temperature. Therefore, almost all solar radiation in winter is utilized to heat water, and surplus solar radiation in summer cannot result in additional energy savings. Thus, the benefits of SWHs in winter may not be less than those in summer.

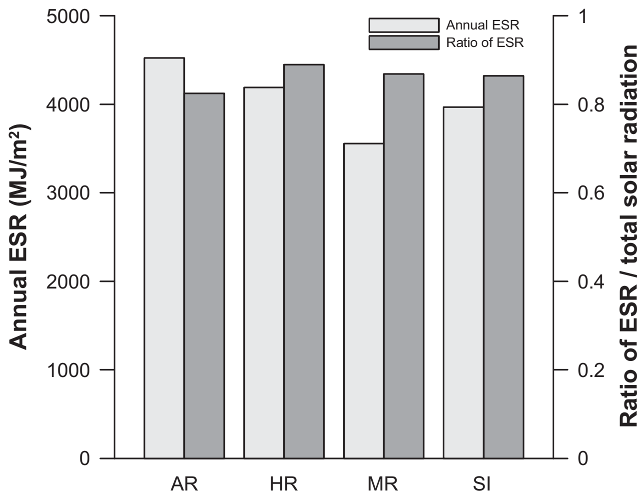


Fig. 4. Annual ESRs and ratios of ESR to total solar radiation in different regions.

Fig. 4 shows the annual ESRs and ratios of ESR to total regional solar radiation in different regions. Although total solar radiation in the AR region exceeds that in the HR region, their ESR values are similar at 4522 and 4194 MJ/m^2, respectively, because the ESR ratio (82%) in the AR region is lower than that (89%) for the HR region.

4. Benefit analysis

The benefits of an SWH include cost savings by replacing conventional energies and pollution mitigation [14]. The cost savings from replacing conventional energies can be estimated by the amount of effective energy generated under annual ESR and the price of replaced energies. Cost savings due to pollution mitigation are determined based on the reduction in the amount of GHGs and air pollutants. The details of the SWH benefit analysis are as follows.

4.1. Cost saving from replacing conventional energies

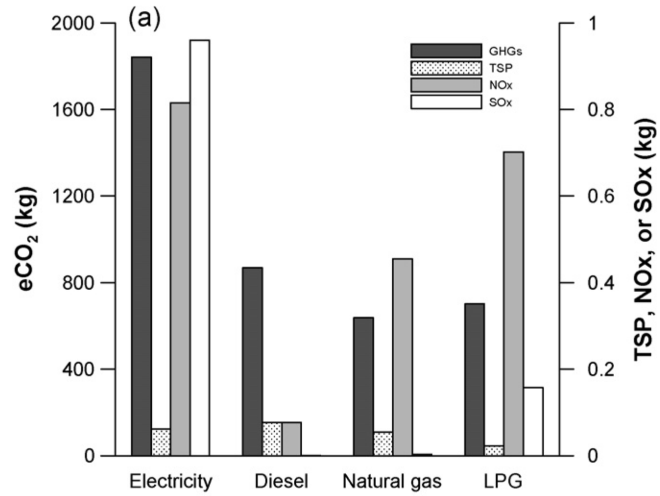
The energy savings by SWHs for different regions in Taiwan are estimated by the followed equation:

$$BE_z = ESR_z \times A \times \gamma_{SWH} \tag{6}$$

$$CBE_z^f = \frac{BE_z}{HV_f \times \gamma_f} \times EP_f \tag{7}$$

where BE_z is total energy reduction in region z; CBE_z^f is cost savings from energy source f (e.g., electricity, diesel, natural gas, and liquefied petroleum gas (LPG)) in region z; HV_f is the heating value of energy source f; γ_f is the heating efficiency of energy source f; and EP_f is the unit price of energy source f. In Eq. (6), total energy reduction is the effective energy generated by an SWH. The monetary benefit of replacing conventional energies is determined using Eq. (7).

Table 2 lists total energy reduction and cost savings by replacing conventional energies for a family SWH, based on the heating value, heating efficiency, and energy price in Table 3 [1,15–19]. Since ESR is the major factor affecting total energy reduction, total energy reductions in the AR and HR regions are markedly higher than that in the MR region. The price of diesel has increased in recent years, and heating water with diesel is expensive. Therefore, using an SWH to replace a diesel heating system can save more than when replacing water heaters fueled with other energies.



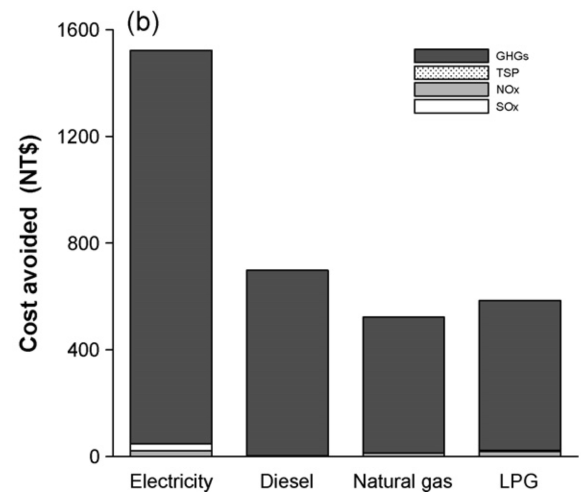


Fig. 5. (a) Pollutant reductions and (b) cost avoided for reducing GHGs and pollutant emissions for different energies in the AR region.

4.2. Cost avoided for GHGs and pollution mitigation

Eqs. (8) and (9) estimate reductions in pollutants emitted by a conventional energy and the cost saving by pollution mitigation, respectively.

$$BP_{p,z}^f = \frac{BE_z}{HV_f \times \gamma_f} \times EF_p^f \tag{8}$$

$$CBP_z^f = \sum_p (BP_{p,z}^f \times TE_p) \tag{9}$$

where $BP_{p,z}^f$ is the reduction in air pollutant p (e.g., GHGs, TSP, NOx, and SOx) when replacing energy source f by an SWH in region z; EF_i^f is the emission factor of air pollutant p for conventional energy f; CBP_z is total cost avoided by reducing GHGs and pollutant emissions in region z; and TE_p is the cost avoided for treating pollutant p.

Table 3 lists the emission factors for each pollutant from four conventional energies—electricity, diesel, natural gas, and LPG. Fig. 5(a) shows the benefit of pollution mitigation by replacing different energies. Roughly 40% of the electricity in Taiwan is generated by coal-fired plants [1]. Coal-fired plants generally emit more pollutants than other power plants. Therefore, replacing electricity has the largest pollution emission reduction. Local costs for reducing 1 metric ton of GHGs, TSP, NOx, and SOx are roughly NT$800, NT$15,365, NT$26,985, and NT$26,242, respectively [20]. Although the unit cost of GHGs removal is significantly lower than those for

Table 2
Total energy reduction and cost saving.

Region	Total energy reduction (MJ)	Cost saving (NT$)			
		Electricity	Diesel	Natural gas	LPG
AR	9044	7481	8842	4400	5281
HR	8388	6939	8200	4081	4898
MR	7112	5883	6953	3460	4153
SI	7938	6566	7761	3862	4635

Table 3
Data for different energy sources.

Source	Heating value [15]	Heating efficiency [16]	Price (2007) [1]	Emission factor				e [19]
				eCO_2 [16]	TSP [17]	NOx [17]	SOx [17]	
Electricity	860 kcal/kWh	90%	2.68 NT$/kWh	660 g/kWh	0.022 g/kWh [18]	0.292 g/kWh [18]	0.344 g/kWh [18]	1.47%
Diesel	8400 kcal/L	80%	27.5 NT$/L	2700 g/L	0.24 g/L	0.24 g/L	0.0009 g/L	9.71%
Natural gas	8900 kcal/m^3	80%	14.5 NT$/$m^3$	2100 g/m^3	0.179 g/m^3	1.50 g/m^3	0.0096 g/m^3	8.86%
LPG	6700 kcal/L	80%	13.1 NT$/L	1740 g/L	0.054 g/L	1.74 g/L	0.391 g/L	8.30%

other pollutants, total cost reduction for GHGs, as illustrated in Fig. 5(b), is the highest because the reduction in GHGs emissions is large.

5. Cost analysis

To assess the applicability of Taiwan's national SWH program, a cost analysis was first implemented. The following equations, similar to those used by Kaldellis et al. [6], are applied to estimate the annual cost of an SWH.

$$AC = (FC + MC - S) \cdot \left(\frac{i \cdot (1+i)^n}{(1+i)^n - 1} \right) \tag{10}$$

$$MC = MR \cdot \sum_{r=1}^{n} \left(\frac{1+f}{1+i} \right)^r \tag{11}$$

$$MR = m \cdot FC \tag{12}$$

$$S = \alpha \cdot A \tag{13}$$

where AC is the annual cost of an SWH for n operating years; FC is initial installation cost; MC is current value of total maintenance cost; S is the government subsidy; i is the discount rate; MR is annual maintenance cost; f is average inflation rate; m is the ratio of annual maintenance cost to initial installation cost; and α is the subsidy rate based on collector area.

In Eq. (10), annual cost of an SWH is estimated based on initial installation cost, total maintenance cost, and the government subsidy. Eq. (11) determines the current value of total maintenance cost based on annual maintenance cost, with an annual increase rate equal to the average inflation rate and local discount rate. Annual maintenance cost is assumed to be a fixed fraction (m) of initial installation cost, as in Eq. (12). In Taiwan, the government subsidy is based on the surface area of a solar collector. Therefore, Eq. (13) determines the subsidy amount by multiplying the subsidy rate by the surface area of a solar collector.

For a family SWH in Taiwan, typical installation cost is roughly NT$66,000; annual maintenance cost is about 3% of installation cost; national discount rate is 1.86%; and the inflation rate is 1.08%. Since a subsidy is an effective policy tool inducing residents to install an SWH, three subsidy rates are compared. The first subsidy rate is zero, and the second is 2250 NT$/$m^2$, which is the current subsidy rate in Taiwan. Some local governments have raised the subsidy rate to 4500 NT$/$m^2$, which is the third rate.

Since the SWHs installed in Taiwan's four regions are similar, the SWH costs for the four regions are assumed the same. Fig. 6 compares annual costs of an SWH with different subsidy rates and years of operation. The annual costs for an SWH operating for 6–15 years are 20–10% of that for an SWH operating for only 1 year. Therefore, ensuring that an SWH can operate for at least 6 years is essential; otherwise, an SWH may not be cost-effective. Furthermore, annual costs and differences in annual costs with different subsidy rates decrease as the operating period increases. Payback periods of an SWH with different subsidy rates are estimated and discussed in the next section.

6. Payback period analysis

The payback period is the duration required for an SWH investment to pay for itself, and can be used to measure the economic feasibility of installing an SWH [21,22]. The payback period is determined by comparing annual cost and annual benefit for an SWH. As mentioned, annual cost of an SWH can be derived by Eq. (6). Annual benefit, as determined by the cost saving by replacing a

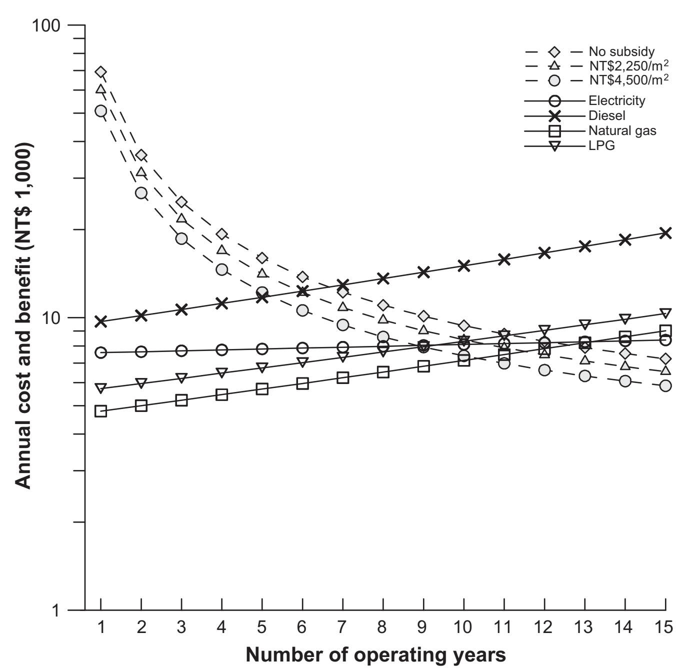


Fig. 6. Annual costs and benefits for varied subsidy rates, replaced different energies, and payback periods in the AR region.

conventional energy, can be estimated by Eq. (14), which is similar to the equation used by Kaldellis et al. [6].

$$AB_z^f = CBE_z^f \times \left(\sum_{r=1}^{n} \left(\frac{(1+e)}{(1+i)} \right)^r \right) \times \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right) \quad (14)$$

where AB_z^f is the annual cost saving by replacing energy f in region z; CBE_z^f, derived by Eq. (7), is the cost saving by replacing energy source f; e is the annual rate of market price change for a replaced conventional energy; and n is the number of SWH operating years. The annual cost and annual benefit vary for different operating years. And the payback period equals the operating years in which annual benefit is equal to or greater than annual cost.

Fig. 6 shows annual costs with different subsidy rates and the annual cost saving by replacing different energies with a typical SWH installed in the AR region. As shown in Fig. 6 and Table 2, the cost saving of replacing diesel is higher than that of replacing other conventional energies because the diesel price has increased substantially in recent years. The annual benefit of replacing electricity during the first few years is higher than that of replacing LPG and natural gas. However, since the price of electricity is controlled by the government and does not increase significantly, the market price change rate, e, for electricity, as listed in Table 3, is smaller than that of other energies. After 14 or 10 years, the annual benefit of replacing electricity is lower than that of replacing LPG or natural gas.

The intersection of the annual cost and annual benefit curves is the payback period. Since energy generated by diesel per dollar is lower than that by other energies, the cost saving for diesel is higher than those for other energies, and the payback period of diesel is shortest. If the price of diesel remains high, the government should encourage those using diesel heating systems to install an SWH.

Since the payback period markedly influences resident willingness to install SWHs, subsidies are frequently provided to shorten the payback period and increase incentive to adopt SWHs. As Fig. 6 shows, in the AR region without a subsidy, the payback period for replacing an electricity water heater is 13 years. When the subsidy rate is NT\$2250/m^2, the payback period is 11 years, better than that for replacing a natural gas water heater. If the subsidy rate is increased to NT\$4500/m^2, the payback period is reduced significantly to 9 years, which is close to that for replacing an LPG water heater. Table 4 lists the payback periods for the four regions under a subsidy rate of NT\$2250/m^2. The payback period decreases as the amount of solar radiation increases. Most payback periods are 11–13 years, excluding those for replacing electricity and natural gas water heaters in the MR region. Those for replacing diesel water heaters are only 6–8 years because the price of diesel and its market price change rate are both high. The cost saving for replacing electricity in the first year is higher than those for replacing natural gas and LPG. However, the payback period for replacing electricity is not shorter than those for replacing diesel and LPG because the local market price change rate, e, for electricity is smaller than those for other energies.

7. National SWH program in Taiwan

To achieve energy independence and reduce GHGs emissions, the government implemented a national program called the National Science and Technology Program for Energy [23]; promoting SWH use is one of the program's primary tasks. The goal of the program is to assist 150,000 households in installing SWHs during 2010–2014. The typical surface area of a household SWH solar collector is 4 m^2 and, thus, approximately 600,000 m^2 of solar collectors will be installed during this 5-year period. Analyzing expected cost and benefits of SWH installation is essential when evaluating the effectiveness of this national program. The benefits of installing SWHs vary markedly as regions have different amounts of solar radiation. The probable SWH distribution is estimated based on historical data of SWH installation [24], sales volume of conventional heaters [25], and the ratio of conventional heaters replaced by SWHs in different regions in Taiwan, as listed in Table 5.

Program effectiveness is evaluated using two approaches. First, nationwide benefit and cost of the program are estimated and analyzed for overall effectiveness. Second, government investment, including subsidy, is compared with public benefit gained by reducing pollutant and GHGs emissions. These two approaches are described in the following sections.

7.1. Nationwide benefit and cost

To analyze nationwide benefit and cost, total annual cost saving from replacing conventional energies and the cost of installing and maintaining SWHs are estimated and compared. Total annual cost saving from replacing a conventional energy in region z, TAB_z, is determined by Eq. (15).

$$TAB_z = PA \cdot RI_z \cdot \sum_f (AB_z^f \cdot H_z^f) \quad (15)$$

where PA is the total estimated area of all SWH solar collectors installed under the program, 600,000 m^2; RI_z is the national ratio of SWHs installed in region z, as listed in Table 5; AB_z^f is the annual benefit of cost saving from replacing energy f in region z, as determined by Eq. (14); and H_z^f is the ratio of installed SWH collectors replacing heaters that use energy f in region z.

In addition to the cost saving of replacing a conventional energy, pollution mitigation is an essential SWH benefit. The annual amount of pollution mitigated, TBP_z, and annual cost avoided for reducing GHGs and pollutant emissions, TAP_z, are calculated by the following equations; where $BP_{p,z}^f$ is GHGs and air pollutant emission reductions, as determined by Eq. (8).

$$TBP_{p,z} = PA \cdot RI_z \cdot \sum_f (BP_{p,z}^f \cdot H_z^f) \quad (16)$$

$$TAP_z = \sum_p (TBP_{p,z} \cdot TE_p) \quad (17)$$

Although a subsidy is a policy cost for the program, it is mainly a monetary transfer of funds from the government to a resident and is not a cost of installing SWHs. The subsidy is therefore not included when estimating national annual cost.

For 15 operating years, the annual cost savings from replacing conventional energy (TAB_z) plus the cost avoided to reduce GHGs and pollutant emissions (TAP_z) is NT\$1534 million. According to the estimated cost savings and cost for implementing the national SWH program, the net benefit for the program is approximately NT\$449 million. As illustrated in Fig. 7, without considering cost of reducing GHGs and pollutant emissions, the program payback period is 12 years. By considering these avoided costs, the payback is reduced to 11 years.

7.2. Governmental subsidy vs. associated benefits

Evaluating the effectiveness of the program and analyzing whether benefits gained from program implementation exceed its costs are important. The primary cost of program implementation is the subsidy provided to residents who install SWHs. This subsidy is paid at the time at which an SWH is installed. The current subsidy rate is 2250 NT\$/m^2. Approximately 600,000 m^2 of SWH collectors will be installed under the program and, thus, the total amount of subsidies is NT\$1350 million.

Table 4
Payback periods under the subsidy rate of NT$ 2250/m^2 for replacing different energies in different regions.

Region	Payback period (year)			
	Electricity	Diesel	Natural gas	LPG
AR	11	6	12	11
HR	12	7	13	11
MR	15	8	15	13
SI	13	7	13	11

Table 5
The SWH installation ratios and ratio for replacing different conventional heaters in different regions.

Region (z)	Installation ratio (RI_z)	Ratio for replacing traditional heater (H_z^f)			
		Electricity	Diesel	Natural gas	LPG
AR	47.6%	32.56%	3.87%	14.02%	49.55%
HR	42.0%	33.26%	1.89%	20.21%	44.64%
MR	10.1%	31.65%	6.63%	27.26%	34.45%
SI	0.2%	23.29%	31.54%	0.00%	45.17%

The major public benefit of SWHs is reducing GHGs and pollutant emissions. Since this benefit is estimated annually, the initial one-time subsidy is converted into an annual value for ease of comparison. The annualized subsidy and annual cost avoided for reducing GHGs and pollutant emissions with different operating years for SWHs are compared in Fig. 8. If an SWH operating period exceeds 12 years, the public benefit of the program exceeds the subsidy.

8. Sensitivity analysis

Since some parameters used in this study, such as collector efficiency, installation cost, and discount rate, may change with technical or economic developments and significantly alter assessment results. The sensitivity analysis is thus implemented, as listed in Table 6. The minimum accepted collector efficiency of an SWH is 50% in Taiwan [12]. According to a solar rating and certification report [26], collector efficiencies for some SWHs exceed 80%. Thus, net benefits with collector efficiencies of 50%, 65%, and 80% are analyzed. The price of an SWH varies; the current range in Taiwan is roughly NT$40,000–89,000, and the typical price is about NT$66,000. Therefore, the prices of NT$66,000, NT$46,200, and NT$85,800, which are 1, 0.7, and 1.3 times the typical price, respectively, are analyzed. The discount rates in last few years varied at 1.25–3.62% [27]. Therefore, discount rates of 1%, 1.86%, and 3% are analyzed.

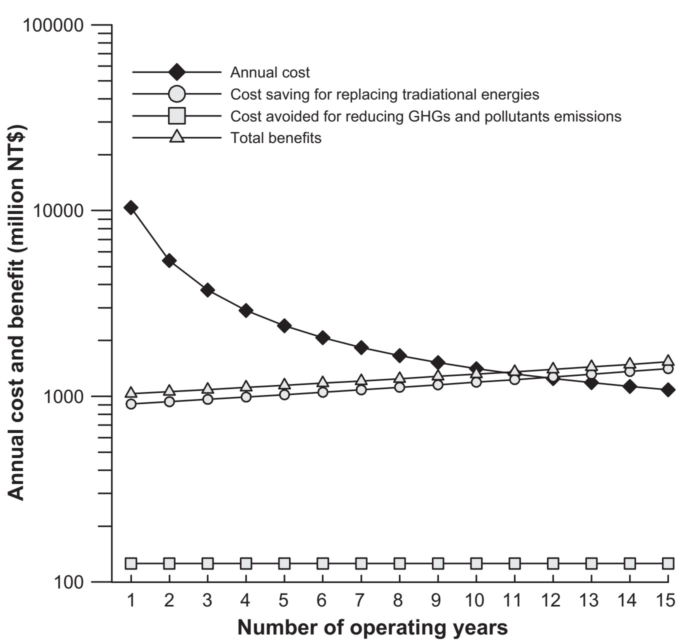


Fig. 7. Annual cost and benefits of implementing the national SWH program.

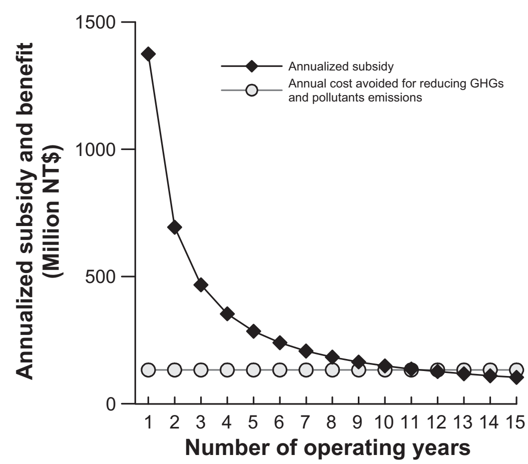


Fig. 8. Annualized subsidy vs. annual benefit for different SWH operating years.

The net annual benefits listed in Table 6 are nationwide benefits estimated with an operating lifetime of 15 years. As heating efficiency increases by 15% from 50% to 65%, net annual benefit increases roughly 38%. However, as collector efficiency increases by 30% from 50% to 80%, net annual benefit increases only 19% because for E-days, as the extra energy from increasing collector efficiency cannot contribute significantly to benefits. If only collector

Table 6
Sensitivity analysis of collector efficiency, installation cost, and the discount rate.

Parameter	Values	Net annual benefit (million NT$)
Collector efficiency	50%	449
	65%	614
	80%	700
Installation cost (NT$)	46,200	775
	66,000	449
	85,800	123
Discount rate	1.00%	511
	1.86%	449
	3.00%	365

efficiency is improved, the net benefit does not increase significantly. However, as collector efficiency increases, the required collector surface and associated installation cost likely decline significantly although predicting this cost reduction is difficult. As installation cost declines by 30%, the annual net benefit can increase about 73%. Therefore, the government should encourage SWH manufacturers to develop low-cost SWHs to increase benefit. Moreover, the low discount rate can increase net benefit and is advantageous for SWH development.

9. Conclusion

Since solar radiation captured today cannot be used later, the conventional method that uses total annual solar radiation may overestimate the energy production of an SWH. This study thus proposed the ESR and E-days based on tap water temperature and solar radiation to improve the SWH energy saving estimation. Total annual solar radiation in the AR region is markedly higher than that in other regions; however, the ESR values of the AR and HR regions are similar. For the AR region, the ratio of ESR to total annual solar radiation is about 82%. If the SWH energy production is estimated based on total annual solar radiation, SWH energy production will be overestimated by 18%. The proposed ESR is expected to improve the estimation.

Two major benefits of installing SWHs are assessed. One is the cost saving generated by replacing conventional energies, and the other is avoiding the costs associated with reducing GHGs and pollutant emissions. The cost saving of replacing conventional energies is roughly 11 times the cost avoided to reduce GHGs and pollutant emissions. The payback periods of an SWH in different regions are also determined. Although total annual solar radiation in the AR region is markedly higher than that in the HR region, the payback periods in the AR and HR regions are close because the ESRs in both regions are similar. The payback period for an SWH replacing a diesel heater is 6–8 years, significantly shorter than those for replacing water heaters powered by other conventional energies because the price/heat unit of diesel is higher than those of other conventional energies.

The annual net benefit for the national SWH development program is approximately NT$449 million. Additionally, GHGs emissions can be reduced by approximately 150,000 tons yearly. By comparing subsidy cost and the benefit of reducing GHGs and pollutant emissions, the payback period for the national SWH development program is roughly 13 years. Increasing collector efficiency can reduce the minimum required solar radiation and increase the number of E-days. However, the additional benefit gained by increasing the collector efficiency from 65% to 80% is less than that from 50% to 65% because the additional energy generated on E-days cannot result in additional benefit.

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